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Comparison of mechanical properties measured on multiple scales

Fuel Cycle Research & Development

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SUMMARY

FeCrAl alloys are being developed for accident tolerant fuels for current light water reactors. Specifically as fuel claddings with enhanced safety. These alloys are being developed to have excellent corrosion resistance in light water reactor coolant environments and structural integrity for longer durations in the case of a loss of coolant scenario where time is critical for safety. Tensile, shear punch, and Vickers hardness testing was performed on neutron irradiated FeCrAl alloys with three variations in composition. Testing was done at room temperature for comparison of the three techniques. FeCrAl alloys in this report were irradiated at Oak Ridge National Laboratory (ORNL) in the High Flux Isotope Reactor (HFIR) to 7 dpa and at 320 °C.

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1. Introduction

Mechanical testing of neutron irradiated materials is difficult due to activation, which requires special handling. Using testing techniques that utilize smaller testing volumes than traditional tensile tests can reduce costs of material development for advanced reactors. Prior efforts have investigated the effect of miniaturization of mechanical testing [1, 2], however, it is not completely established when these results can be trusted.

One application where mechanical testing of small sample volumes is useful is testing various compositions of FeCrAl alloys. Among several candidates for "accident tolerant" fuel cladding, FeCrAl alloys are among the top choices due to their superior high temperature oxidation resistance, aqueous corrosion resistance, low radiation-induced swelling, and tolerance to loss-of-coolant accident conditions [1-4]. It is important to note that despite their higher neutron absorption cross-section compared to zirconium-based alloys, their mechanical and chemical stability over a range of environment make this alloy and attractive candidate to others (i.e. SiC-based cladding).

2. Materials and Methods

2.1 Materials

Neutron irradiated FeCrAl alloys were in the form of SS-J2 miniature tensile specimens with 0.5 mm thickness with compositions given in Table 1. Notably the Cr content of each alloy is significantly different, and ranges from 10 to 15 weight %. These samples were machined from wrought plates. The plates were processed based on optimized thermo-mechanical treatment [3].

Table 1: Compositions of alloys in weight %.

Material	Alloy ID	Fe	Cr	Al	Y
F1C5AY	522	bal	10.0	4.8	0.038
B125Y	2522	bal	12.0	4.4	0.027
B154Y-2	5422	bal	15.0	3.9	0.035

The samples were irradiated at Oak Ridge National Laboratory (ORNL) in the High Flux Isotope Reactor (HFIR) to a dose of 7 dpa at an irradiation temperature of 320 °C [4]. After irradiation, the SS-J2 geometry samples were tensile tested, and detailed in a previous report [5]. The grip sections from the tensile tested samples were used for the shear punch testing to provide a direct comparison between the two mechanical testing methods. Tensile tests were done by shoulder loading the specimen grip sections.

2.2 Tensile testing

Tensile tests were conducted on SS-J2 geometry dogbones with 0.50 mm thickness. The samples were shoulder loaded using an Instron 5567 screw driven load frame inside a hot cell in Wing 9 at the CMR facility at Los Alamos National Laboratory. Figure 1 shows the shoulder loading fixture used. Testing was done at room temperature and at a nominal strain rate of 10^{-3} s^{-1}.

Figure 1: Shoulder loading tensile test fixture.

2.3 Shear punch testing

Shear punch testing was carried out with a fixture seen schematically in Fig. 2(a) and (b). Figure 2(a) shows the sample is held in place on top and bottom, the 1 mm diameter punch is pressed against the sample and is used to punch out a disk. Tensile specimen grip sections of SS-J2 geometry (0.50 mm thick), Fig. 2(c), were subjected to the 1 mm punch in uniaxial compression. To hold the grip sections in place an insert for the fixture is used, shown in the schematic Fig. 2(b). The punching is carried out on an Instron 5567 screw driven load frame located in the hot cells in Wing 9 of the CMR building at LANL. The raw load-extension data is transformed into an effective shear stress-shear strain curve via simple calculations. The effective shear stress (ESS) is the *load/area*, with *area* being the deformed region, which is the *circumference of the punch* divided by the *thickness of the sample*. This ESS vs shear strain curve can be correlated to tensile yield and UTS via simple relationships, more details can are provided in the references [6-9]. Strain is calculated as displacement divided by sample thickness. Each sample is measured before testing with a micrometer in the hot cells. For the shear punch tests, the amount of strain during work hardening is given as work hardening strain, which is the amount of strain between the strain at the 1 % offset and the strain at the ultimate tensile strength.

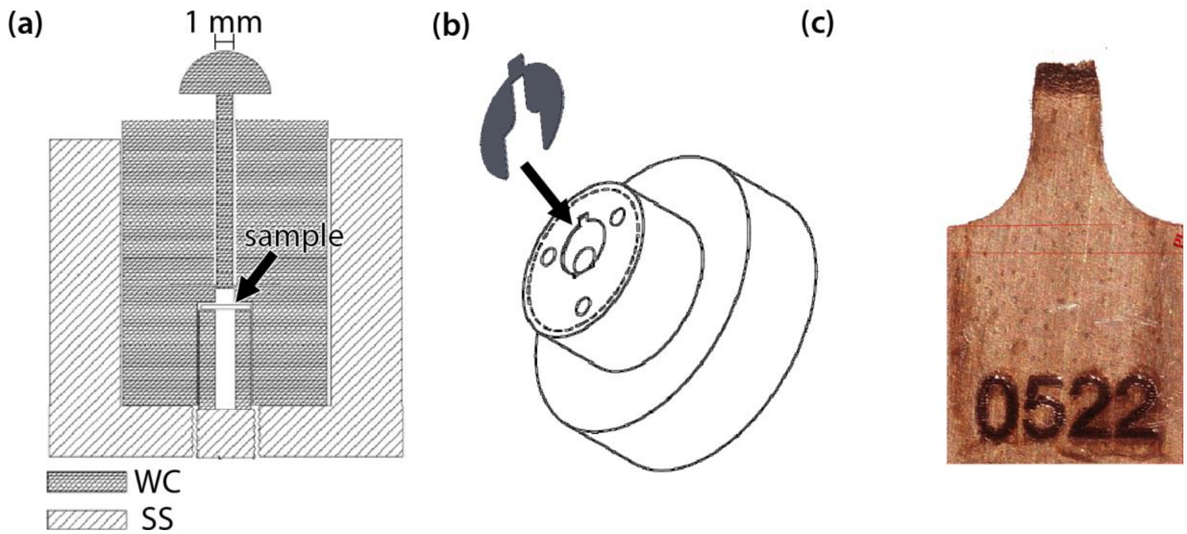

Figure 2: (a) Schematic of Shear Punch Test fixture for grip sections of miniature tensile samples, punch size is 1 mm in diameter. (b) Schematic of shear punch test fixture and insert to accommodate grip sections of miniature tensile samples. (c) Grip section of miniature tensile sample post-tensile testing.

2.4 Hardness testing

Hardness testing was performed on the punch outs from the shear punch tests. Samples were prepared such that the sample surface was flat and perpendicular to the hardness testing. To achieve this, the punch out was glued (with super glue) to a 1.5 inch diameter and 1.0 inch tall aluminum cylinder. Mechanical polishing using 600, 800 and 1200 grit grinding paper was performed on the sample while checking the sample for being flat and parallel to the back of the aluminum block. Polishing was then performed using 3 μm diamond solution before a final polish with 1 μm diamond solution.

Standard Vickers hardness indentations were conducted using a 500 g load and according to ASTM standard E92-17 [10]. Measurements of the indentations to calculate hardness were taken manually using optical microscopy with a 50x lens. An image of the hardness tester is presented in Fig. 3.

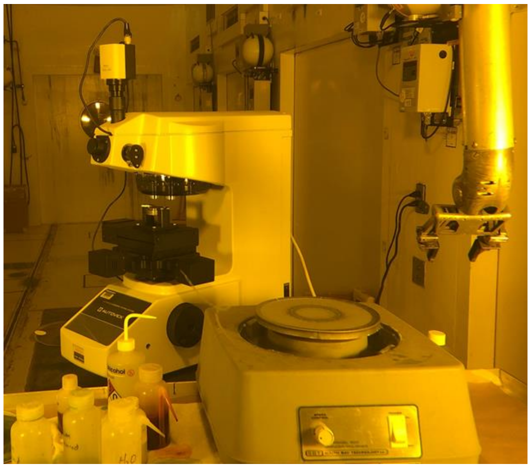

Figure 3: Hardness tester and mechanical polishing setup in Wing 9 hot cell corridor at CMR facility at LANL.

3. Results and Discussion

3.1. Mechanical properties

3.1.1 Tensile Testing

Tensile testing results are summarized in Table 2, and include yield and ultimate strength, uniform elongation and total elongation. The strength (both yield and ultimate) increased with increasing Cr content. Additionally, none of the samples exhibited work hardening. Further details may be found in the prior report by Saleh et al. [5].

Table 2: Tensile test results from previous report [5].

Material	Sample	T irr °C	dose (dpa)	Test Temperature	Yield (MPa)	Ultimate tensile strength (MPa)	Uniform Elongation strain	Total Elongation strain
F1C5AY	522	320	7	RT	775	775	0.003	0.079
B125Y	2522	320	7	RT	830	833.4	0.0025	0.06
B154Y-2	5422	320	7	RT	840	840.2	0.002	0.072

3.1.2 Shear Punch

Shear punch testing was conducted on the grip section of tensile specimens in order to compare shear punch to tensile testing. The tensile samples were shoulder loaded to the grip sections which provided a location for shear punch of undeformed material. Stress displacement plots for the three shear punch tested FeCrAl alloys, both irradiated and control materials are presented in Fig. 4. All three alloys showed similar mechanical responses. For the irradiated material, work hardening and strain during work hardening were minimal. The control samples, however, exhibited some work hardening after yielding. These results are consistent with the prior tensile tests performed on the same samples [5].

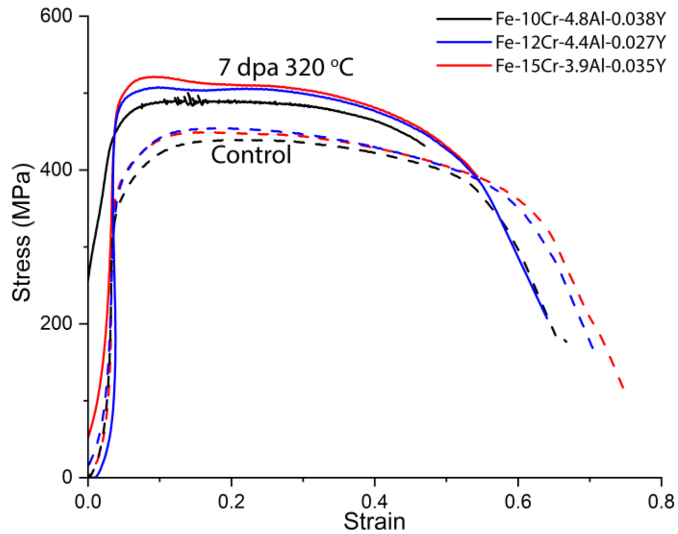

Figure 4: Shear punch stress vs displacement for the three FeCrAl alloys.

Shear punch results are summarized in Table 3. For the irradiated material, the shear punch results compare very well to the tensile results. After yielding, work hardening and the amount of strain during work hardening are minimal. Strength, both yield and ultimate, increase with Cr content. Additionally, work hardening increases with decreasing Cr content which was not observed in the tensile tests.

Table 3: Shear punch results on FeCrAl samples.

Material	Sample	T irr °C	dose (dpa)	Test Temperature	1% offset (MPa)	Ultimate shear strength (MPa)	Work Hardening Strain	Δσ
F1C5AY	0522	320	7	RT	444	489	0.10	45
B125Y	2522	320	7	RT	482	507	0.06	25
B154Y-2	5422	320	7	RT	490	521	0.05	31
F1C5AY	0535	NA	0	RT	359	439	0.18	80
B125Y	2535	NA	0	RT	381	454	0.15	73
B154Y-2	5435	NA	0	RT	399	449	0.12	50

Shear punch test results can be used to extract mechanical properties that are normally determined with tensile tests including: yield, ultimate strength, and work hardening. The yield strength for both shear punch and tensile tests can be compared by a simple linear relationship according to

Guduru et al. [9]. Tensile yields presented here were a factor of 1.73 ± 0.02 greater than shear punch yield which is comparable to 1.77 previously reported by Guduru et al. For ultimate strength, tensile results were a factor of 1.61 ± 0.03 greater than the shear results which is different from the factor of 1.8 reported by Guduru et al. A possible avenue to explore for the divergence with respect to the ratio for ultimate strength between the two studies could be the amount of work hardening, which is less in this study.

3.1.3 Hardness

Hardness testing was conducted on one sample, B154Y-2, which was irradiated to 7 dpa at an irradiation temperature of approximately 320 °C. Eleven Vickers hardness indentations were taken on the 1.0 mm shear punch out disk and according to ASTM standards [10]. The average value was 279 ± 5 HV. Comparing the hardness value to the tensile results gives a relationship between yield stress and hardness of $\sigma_{ys} = 3.0 * HV$. That relationship is consistent with prior studies relating yield strength to hardness [11-13].

4. Conclusions

Tensile, shear punch and Vickers hardness testing were conducted on the same irradiated FeCrAl material. This was done by performing shear punch on tensile grip sections, then hardness testing on the punched out disks. For the irradiated FeCrAl, shear punch was able to provide yield and ultimate strength and work hardening behavior consistent with the tensile tests. The one observation that differed slightly was limited work hardening was observed in the shear punch tests and no work hardening was observed with the tensile tests. When comparing the hardness tests to the other techniques, yield strength could be calculated using the relationship $\sigma_{ys} = 3.0 * HV$, which is consistent with prior studies. However, ultimate strength and work hardening behavior could not be extracted with hardness testing.

5. References

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